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A K-BAND IMAGE OF THE GRAVITATIONAL LENS SYSTEM 2016+112

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ABSTRACT

A new K-band (2.0–2.4 μm) image of the gravitational lens system 2016+112 gives the clearest view yet obtained of the two lensing galaxies, which have K magnitudes of 17.2 and ~ 18. The fainter galaxy is extremely red, with $r-K \approx 7.7$ mag, and while no spectroscopic redshift is available for it, estimates based on colors suggest a redshift significantly greater than that of the brighter galaxy. This has important consequences for models of this system.

1. INTRODUCTION

The gravitational lens system 2016+112 has at least seven components (see Fig. 1; Lawrence *et al.* 1984; Schneider *et al.* 1985; Schneider *et al.* 1986; Schneider *et al.* 1987; Heflin *et al.* 1991): two quasar images A and B separated by 3″.4; a much fainter image C′ ∼2″ from B such that ABC′ is roughly a right triangle; a giant elliptical galaxy D near the centroid of ABC′; a second galaxy C, nearly coincident with C′, whose radio core is the brightest radio component in the system; and two fuzzy patches of Lyman α emission A_1 and B_1 (Schneider *et al.* 1986, 1987). The redshift of the quasar and Lyman α clouds is 3.2733, while that of galaxy D is 1.01 (Schneider *et al.* 1986). The redshift of galaxy C is unknown.

Given its mass and position, galaxy D must produce multiple images of the distant quasar; however, only with a highly contrived mass distribution could D by itself produce a third image C′ such that BC′ is almost perpendicular to AB. Models of 2016+112 with two lenses at different redshifts reproduce the gross features of the system (Narasimha *et al.* 1987; Narasimha & Chitre 1988), but cannot be fully developed until the redshift of the second galaxy and its position relative to that of the nearly-coincident third image are known.

Based on a K-band (2.0–2.4 μm) image of 2016+112, Langston *et al.* (1991) proposed a model with a single galaxy lensing a core-jet structure in the quasar. In that model, A and B are interpreted as images of the core of the distant core-jet quasar, and C is interpreted as the highly magnified image of the jet. Two objections can be raised to this model. First, it does not account for the image C′ seen most clearly in an image taken through a narrow filter that includes the Lyman α line (Schneider *et al.* 1986). Second, it requires a jet spectral index flatter than that of the core, in conflict with VLBI observations of 2016+112 (Heflin *et al.* 1991), and unlike other known radio sources.

We have also imaged 2016+112 in the K band. Our image, obtained in better seeing with much finer sampling of the seeing disk, has much higher effective resolution than that of Langston *et al.*, and demonstrates conclusively the existence of two galaxies.

2. OBSERVATIONS AND ANALYSIS

2016+112 was observed on 5 July 1990 with the Caltech 58×62 InSb array camera at the Cassegrain focus of the Hale telescope. The pixel size is 0″.314. A series of ten exposures was made with the 2016+112 system in four different locations on the array separated by about 6″. (If the object were always observed at the same region on the array, the sky, which completely dominates the total signal, would have to be interpolated through that region. Even small fractional errors in the flat would then translate into large absolute noise levels in that region. By placing the object in different locations, the dominant sky background is determined and removed directly at each pixel.) Total integration time was 6120 s. A relatively bright star about 7″ north of A in each image allows transfer of photometric calibration to, and determination of the effective point spread function in, the final processed image. Conditions were photometric, with overall calibration errors estimated at 0.05 mag. The average FWHM of the bright star in the ten exposures was 0″.75. Telescope tracking was controlled by an offset autoguider.

Individual images were flattened and corrected for nonlinearity. The sky level subtracted from each image was an average of those portions of the individual frames that contained no sources in the regions near 2016+112 or the nearby star.

Since the pixels of the array are relatively large compared to the seeing disk, registration of individual images by integral pixel shifts would have seriously degraded the resolution. Accordingly, the images were rebinned to 0″.0314 pixels using bilinear interpolation, shifted by integral (small) pixels according to the relative guider offsets (i.e., the row and column components of the offset rounded to the nearest 0″.0314), and averaged. The result is shown in Fig. 2 (Plate 1). Alignment of individual images according to centroid positions of the bright star rather than guider offsets gives essentially the same result.

The field star ∼7″ north of 2016+112 is well-fit by a Gaussian of FWHM 0″.92×0″.78 at a position angle (P.A.) of −45° (see Table 1). This distortion is consistent with known astigmatism of the 200″ mirror. A Gaussian fit to A without constraints gives a FWHM of 1″.03×0″.70 at P.A.

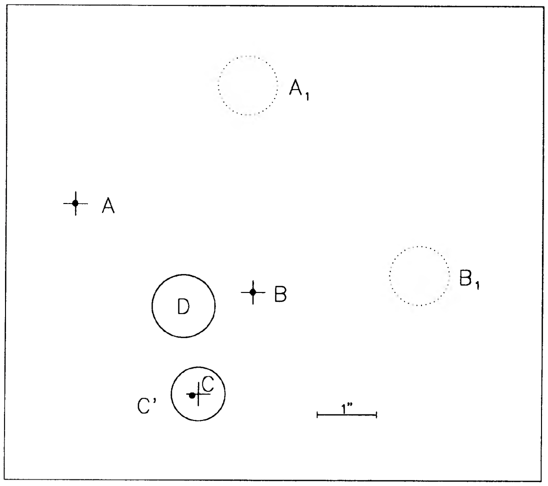

FIG. 1. Geometry of 2016+112. North is to the top, east to the left. Radio sources are marked with a plus sign, spatially unresolved emission line sources with dots, and optically extended objects with circles. Regions A_1 and B_1 are dotted to indicate that they, like A, B, and C′, have strong optical emission lines. The exact position of the third image C′ (dot) relative to galaxy C (plus sign centered in circle) is not known.

$=-30°$, but A is fit almost equally well by a Gaussian with the same width and orientation as the Gaussian fit to the star. The position difference between these two fits to A is only 0″01, and the volumes of the Gaussians differ by only 3%. B, C, and D overlap, and were fit as follows: fit D alone; fix D and fit a second Gaussian to B; fix D and B and fit a third Gaussian to C; finally fix C and refit D and B. This final step was tried both with the width of B (three parameters) fixed to that of the star, and with the width of B free to vary. The width of B in the latter case was 1″59 ×0″88 at P.A. $=-16°$, and the volume was two-thirds greater than in the former case.

For nonoverlapping objects higher photometric accuracy is obtained by integrating the background-subtracted image beyond the wings of the object than by finding the volume of the best-fit Gaussian. B, C, and D are too close to each other to allow this; however, the sum of pixel values over the image of the star differed from the volume of the best-fit Gaussian by only 3%, less than the uncertainty in the calibration. Similar errors can be expected for A and B, while larger errors are likely for extended components C

TABLE 1. Positions and photometry.

	Positions Relative to A				Parameters of Gaussian Fits[c]			
	Radio[a]		Infrared[b]					
Component	α	δ	α	δ	Amplitude	FWHM	P.A.	K(mag)[d]
Star	...	...	−0″96	6″80	12.06	0″91×0″77	−45°1	16.08
A	0″00	0″00	0.00	0.00	1.00	fixed to star		18.78
B	−3.00	−1.49	−3.01	−1.46	1.39	fixed to star		18.42
C+C′	−2.09	−3.21	−1.99	−3.24	1.15	1.34×0.93	−78.7	18.00
D	...	...	−1.83	−1.73	2.74	1.16×0.96	−56.8	17.19

[a] From Lawrence *et al.* 1984. Radio position errors are 0″01.

[b] Calculated from Gaussian fits to the composite image, assuming precise north-south alignment of the array columns and an *a priori* image scale of 0″314/pixel. Because of the small separation and overlap of the various components of 2016+112, uncertainties in these assumptions of 0°1 in alignment and 0″02/pixel cannot be improved with the present image. Formal uncertainties on the relative infrared positions are 0″03.

[c] Amplitudes are relative to A. Uncertainties on widths are 0″02 except for C, which is about 0″03.

[d] Determined from Gaussian fits; uncertainties of ~ 0.05 mag are dominated by overall calibration. As mentioned in the text, the Gaussian approximation to overlapping components may lead to systematic errors that are larger.

TABLE 2. Relative fluxes of components of 2016+112.[a]

Date	Frequency or Band	A/B	(C+C′)/A	(C+C′)/D	C′/(C+C′)$_{\rm est}$[b]
1982 Feb	5 GHz	0.94	3.10	...	0.05
1984 May	5	0.94	3.21	...	...
1987 Jul	5	0.96	3.24	...	...
1983 Oct	r (0.6–0.7 μm)	1.07	...	...	...
1984 Jul	g (0.45–0.55)	1.69	<0.30	...	...
	r (0.6–0.7)	1.16	0.24	>0.25	0.71
	i (0.7–0.9)	1.33	0.35	0.14	0.49
1990 Jul	K (2.0–2.4)	0.77	2.25	0.45	0.08

[a] Based on measurements given in Schneider *et al.* 1985, Langston *et al.* 1987, and this paper.

[b] Estimated assuming that C′/A = 0.17 as measured by Schneider *et al.* 1986 in a narrow-band filter centered near redshifted Lyman α.

and D. For consistency, the magnitudes of all components in Table 1 were determined relative to the star by comparing the volumes of the Gaussian fits.

The apparent magnitude of the star was found in each of the individual images relative to the stars given in Elias *et al.* (1982), and the average magnitude adopted for the star in the composite image. Calibration uncertainties are estimated to be 0.05 mag.

Except for galaxy C, the photometry is consistent with the seven-parameter fit of Langston *et al.* (1991). Langston *et al.* give K magnitudes for C ranging from 19.2 to 22.4, depending on the number of free parameters in their fits, compared to our magnitude of 18.0. In each case, however, they assume that C is unresolved, and do not consider the third image. Given our advantage in both seeing and pixel size, we believe our measurements of C to be more accurate.

The image in Fig. 1 gives the best view yet obtained of C, the second galaxy in the 2016+112 system. Compared to the other components, C is much stronger in the K band than in the optical bands (see Table 2), allowing a more reliable determination of the position of C+C′ than can be achieved at shorter wavelengths.

The centroid of C+C′ is frequency dependent because the fraction of light in the C+C′ complex contributed by the third image C′ is frequency dependent. This fraction can be estimated (Table 2) by making the reasonable assumption (for gravitational lensing) that the flux ratios of images are independent of frequency, i.e., that C′/A has the same value of 0.17 in the i and K bands as it does in the Lyman α line (Schneider *et al.* 1986). Under this assumption, about 8% of the light from C+C′ in the K band is due to the third image, compared to about 5% at 5 GHz. In both cases the third image contributes a small fraction to the total intensity, and should not introduce large offsets between the infrared and radio centroids.

The 0″1 offset between radio and infrared positions of C+C′, therefore, is unlikely to be caused by C′. Although somewhat larger than the formal errors in both radio and infrared fits, it is still only one third of a pixel. In view of the inherent shortcomings of Gaussian fits to elliptical galaxy images, we conclude that this offset is consistent with the identification of the flat spectrum radio source C as the core of the galaxy seen in the K band.

The interpretation of 2016+112 as a two-lens system depends on a clear demonstration that C is resolved. Since galaxies are in general not well-represented by Gaussians, the fits summarized in Table 2 are perhaps insufficient proof of resolution. Figure 3, however, shows slices

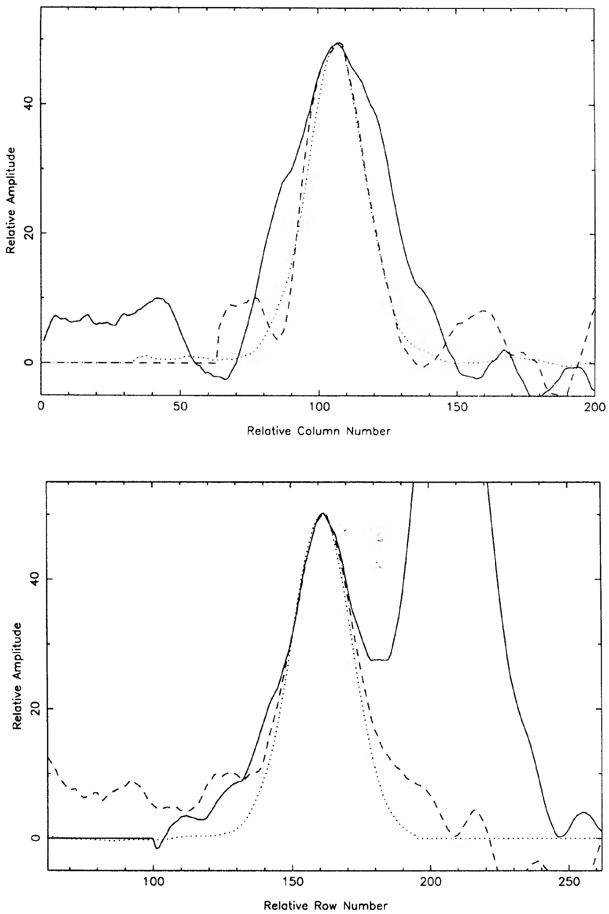

FIG. 3. (a) East–west profiles through C (solid line), A (dashed line), and the nearby star (dotted line), formed by summing nine rows of the image in Fig. 2 centered on the components. (b) North–south profiles formed by summing nine columns.

through C+C′, A, and the nearby star in the east–west and north–south directions (11° from the major and minor axes of the Gaussian fit to C). The north–south slices through A and C are similar in the center, but C is wider below the 50% level. C is clearly wider than A at every level in the east–west direction. In both directions, A and the star have similar profiles. As discussed above, the contribution of the third image cannot account for the width of C+C′. We therefore do not doubt that C is a galaxy.

Galaxy C is much redder than galaxy D. As shown in Table 2, (C+C′)/D=0.14 in the i band, and 0.45 in the K band. After the contribution of C′ to C+C′ is subtracted, C/D=0.07 in i, and 0.41 in K. In terms of colors, $(i-K)_C=6.6$ mag, $(i-K)_D=4.7$ mag, $(r-K)_C=7.7$ mag, and $(r-K)_D>5.8$ mag. The $r-K$ color of C is higher than any found by Elston *et al.* (1991) in a 2 μm selected sample of hundreds of galaxies. Thus C is at the red extreme of a red population that appears at $K \gtrsim 17$ mag and $R-K>4.5$ mag.

TABLE 3. Photometry of the galaxies in 2016+112.[a]

Component	r	i	K	$r-K$	$i-K$
C+C′	24.5	24.0	18.00	6.5	6.0
C (estimated)	25.8	24.7	18.09	7.7	6.6
D	>23	21.90	17.19	>5.8	4.7

[a] Based on measurements given in Schneider *et al.* (1985) and this paper. All entries are magnitudes.

3. DISCUSSION

The K image appears to be entirely consistent with the interpretation of 2016+112 that A, B, and C′ are images of a distant quasar formed by two intervening galaxies, C and D. Two key quantities remain undetermined: the precise position of the third image C′ relative to galaxy C; and the redshift of C. While the K-band image provides no information about the former quantity, the additional color information now available for C gives some hints about the latter. Table 3 summarizes photometric results for C and D.

Estimating redshifts from colors is a dangerous pastime. Such estimates are based on the assumption that the object in question is like objects previously observed, an assumption that is often wrong in the most interesting cases. In the case of 2016+112, however, even a crude estimate would be extremely valuable if it showed that C was or was not at approximately the same redshift as D. The reason for this is that models with lenses at substantially different redshifts have not been required in any other lens systems, and have therefore been only minimally explored (Narasimha, *et al.* 1987). Since we have been unable to measure a redshift for C directly, a modest attempt seems in order.

Before turning to C, consider D as an example. Schneider *et al.* (1985) estimated that $z_D \lesssim 1$, by comparing lower limits on g and r and a measurement of i to what would be expected from a nearby giant elliptical at various redshifts. This turned out to be a good estimate of D's redshift of 1.01, for as noted by Schneider *et al.* (1986) the spectrum of D is quite similar to that of the Virgo elliptical NGC 4889.

The redshift of C could be estimated in the same way. It is easier, however, to assume that the spectral energy distributions of both C and D are identical to that of NGC 4889, and to calculate the redshift z_C at which $\Delta \equiv (i-K)_{z_C}-(i-K)_{z=1.01}=1.9$ mag, the observed difference between C and D (Table 3). A spectrum of NGC 4889 (kindly provided by D. Schneider) was used for this purpose. From $z_C=1.01$ to $z_C \approx 1.5$ (the redshift at which the extreme blue end of the NGC 4889 spectrum passes into the i band) Δ increases monotonically, but only reaches 1.01 mag at $z=1.5$. Even without knowledge of the ultraviolet spectrum of NGC 4889, we can say that $z_C>1.5$.

NGC 4889 is not a radio galaxy, but in a similar exercise based on the spectral energy distributions of the reddest radio galaxies, Lilly *et al.* (1985) predict $r-K=7$ mag and $K=18$ mag at $z=2$. This is obviously consistent with the lower limit derived from NGC 4889. From these results, therefore, we conclude that if the SED of C is like that of the reddest galaxies seen at low redshifts, $z_C \gtrsim 2$.

Another way to estimate the redshift of C is to find objects of similar apparent magnitudes and colors. McCarthy *et al.* (1991) report: a $K=16.89$ mag radio galaxy at $z=2.016$ with $r-K=7.31$ mag in a central core; two $K=17.7$ mag "companions" with $r-K$ of 7.0 and 7.3 mag, about 13″ away from a radio galaxy at $z=2.630$; and two companions with $K=18.5$ mag and $r-K>6$, and $K=19.5$ mag and $r-K>5$ mag, within 15″ of a radio galaxy at $z=2.427$. All of the radio galaxies are Molonglo sources with $S_{420\ \mathrm{MHz}}>0.9$ Jy; the companion galaxies have no detected radio emission. While the redshifts of the nearby companions are not known, their positions, magnitudes, and colors led McCarthy *et al.* to consider the possibility that these galaxies are bright galaxies in a cluster dominated by the radio galaxy.

Lilly (1989) gives a $K-z$ Hubble diagram for 3C ($S_{178\ \mathrm{MHz}}>10$ Jy) and B2 ($S_{408\ \mathrm{MHz}}>1$ Jy) galaxies that ends at about $K\approx 18$ mag with $z\approx 2$. These galaxies are significantly bluer than C, giving yet another indication that C is at the red extreme of known galaxies.

Since C is a compact radio source, it is possible that some of its optical and infrared emission may be from a Doppler-boosted synchrotron component. The fuzzy appearance of C and the lack of a strong unresolved core, however, suggest that C's optical and infrared emission is dominated by starlight. The flux density of C alone has not been measured at low frequencies where emission is isotropic, but the flux density of the entire 2016+112 system at 327 MHz is less than 100 mJy (Langston *et al.* 1987). Thus C is at least two orders of magnitude below the flux density cutoff of the 3C catalog, and one order of magnitude below the flux density of the weaker radio galaxies studied by McCarthy *et al.* (1991) and Lilly (1989). C's isotropic radio luminosity is therefore low compared to that of typical high redshift radio galaxies. On the other hand, it is much higher than the radio luminosity of the radio-quiet "companions" found by McCarthy *et al.* (1991), which seem to have optical and infrared properties much like their high-radio-luminosity cousins. Neither the difference in radio structure between C and these other radio galaxies nor the lower radio luminosity of C obviously invalidates the comparison we have made for the purpose of estimating a redshift.

In summary, if the spectra of C and D are identical with that of nearby giant ellipticals, or if C is like known galaxies almost as red, C is at a substantially higher redshift than D, perhaps 2 or greater. The observed colors of C are extreme compared to most galaxies, but not extreme compared to a subset of high-redshift radio galaxies. Nor are they so different from the colors that would be observed if the reddest nearby giant elliptical galaxies were moved to high redshifts.

Our earlier caution about color-estimated redshifts is relevant, of course, and it is possible that galaxy C is the first of a new category of extremely red, *low* redshift radio galaxies. It is also possible that our estimate of the contribution of the third image C′ to C+C′ is in error, and C is not as red as our estimates. This would have little effect on our conclusions, however, because C+C′ still has $r-K=6.5$ mag. Considering all the data, we think it reasonable to conclude that C is at significantly higher redshift than D, at $z\gtrsim 2$.

If this conclusion is correct, then D will lens C as well as the quasar at $z=3.2733$. The effects of this lensing would be dramatic if part of C lay inside D's radial caustic, but there is no evidence in the morphology of C that this is the case, nor is it likely given the angular separation of C from D. Magnifications of parts of C by up to a factor of two or so would not be terribly surprising, but unless regions of quite different color were deferentially magnified there would be little or no effect on the previous color arguments. Many details of the lensing geometry in 2016+112 will only be understood when a spectroscopic redshift has been measured for C.

From a lensing standpoint it is the combination of redshift and mass, rather than redshift alone, that is important. Even if it turns out that the rest-frame colors of extremely red galaxies such as C are like those of nearby ellipticals, the masses may be quite different. If C really is at high redshift, it may provide important lessons in the star formation history of red galaxies. Once a spectroscopic redshift is known, mass estimates of C from lensing models can be compared with masses for nearby galaxies. Model estimates of the mass of D may be important for the same reason.

A spectroscopic redshift for C can be anticipated with telescopes under construction, and the offset between C and C′ may yet be found with a modified *HST*. Until those quantities are known there can be no definitive model of 2016+112.

4. SUMMARY

The *K*-band image shows clearly that C and D are separate galaxies, and supports the interpretation of 2016+112 as a two-lens system. Estimates of the redshift of the second galaxy C under the assumption that its spectral energy distribution is the same as that of the reddest nearby galaxies, or that C is like other known high-redshift radio galaxies, suggest that it is much greater than the redshift of D.

The new image with its small field of view contains no information on whether either of the two lenses belongs to a cluster; however, earlier CCD images showed no hints of clusters. Thus, models with two lenses at different redshifts are appropriate for this system. Once a spectroscopic redshift can be measured for C, mass estimates for C and D from models may be useful in understanding the nature of extremely red galaxies at high redshifts.

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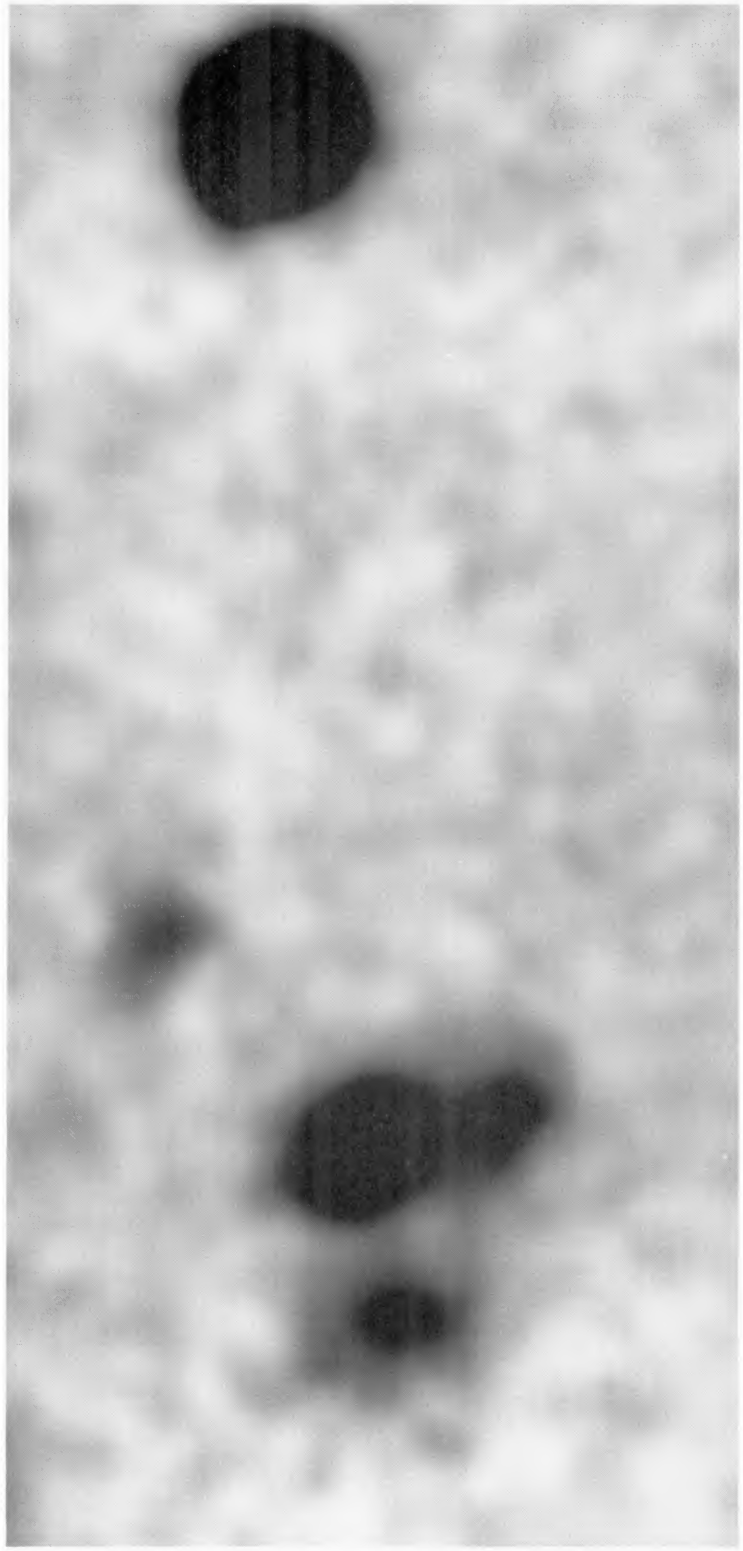

FIG. 2. K-band image of 2016+112 obtained by combining ten exposures as described in the text. The total integration time was 6120 s. Pixels in this composite are 0."0314 square. Pixels in the individual exposures were 0."314. North is at the top, east is to the left.

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